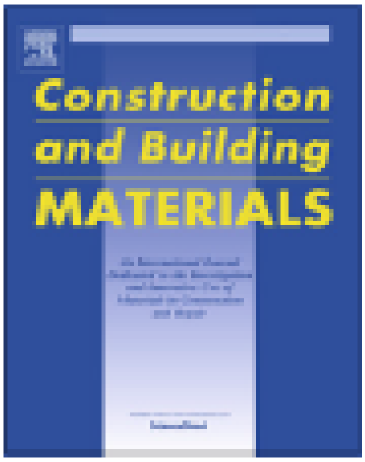

Advanced Analytical Techniques in Fatigue and Rutting Related Characterisations of Modified Bitumen: Literature review

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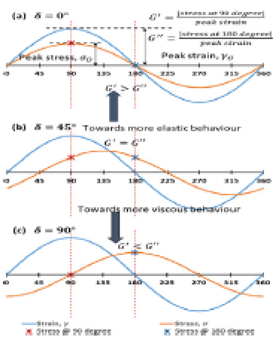
HIGHLIGHTS

- Addressing the property-related performance of bituminous binders.
- Using only a single binder property cannot adequately describe the binder contribution.
- The modified binders have a complex behaviour depending on stress degree and rate.
- The fatigue failure point should be identified based on fundamental criteria.

GRAPHICAL ABSTRACT



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Abstract:

Fatigue and rutting are the two major failure distresses in flexible pavement that affect significantly the serviceability of pavement. The properties of bitumen have a direct effect on controlling the fatigue and rutting distresses. Because of the increase in vehicular loading and repetitions, the modification of neat bitumens becomes a widespread practice to improve their mechanical properties. Any improvements obtained from developing modified binders need be reflected by fundamental testing parameters. The empirical testing methods and Superpave grading procedure that were developed mainly for unmodified bitumens have failed in many cases to predict the performance of modified bitumens. Evaluation the influence of such modifiers needs be based on characterising accurately the inherent resistance of binders to fatigue and rutting damage. The most advanced tests and fundamental analysis methods for characterising the fatigue and rutting properties of binders, are discussed and presented in this paper. These include fatigue and ductile fracture evaluation of binders using time sweep and double-edged notched tension (DENT) tests. For bitumen rutting evaluation, the SHRP rutting parameter, Shenoy rutting parameter, ZSV and MSCR are discussed. The dynamic shear rheometer (DSR) has been largely used to characterise fundamentally the viscoelastic properties of bitumens. A detailed description of the main elements associated with the DSR and Dynamic Mechanical Analysis (DMA) are also presented in this paper.

Keywords: fatigue, rutting, rheological properties, modified bitumen, dynamic shear rheometer

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1. Introduction

Asphalt mixtures are the main materials used to construct the bituminous layers of flexible pavements. An asphalt mixture is a composite material consisting of aggregate and bitumen. The aggregate particles form the skeleton matrix that is cemented together by bitumen. Bitumen is a viscoelastic, thermoplastic, complex material that behaves differently with temperature and loading time. It is purely viscous at high temperatures and/or under slow moving loads; at those conditions, the materials become prone to permanent deformation (rutting). It is also totally elastic and eventually brittle at low temperatures and/or high rapid loads and subsequently the materials become apron to the low-temperature cracking. However, within 10 to 35 ℃ in-service pavement temperatures, where the pavement is subjected to a considerable part of its repetitive traffic loads, the main mode of distress is fatigue cracking. The asphalt pavement is adequately hard and elastic to dissipate excessive repetitive loads through crack initiation and eventually propagation.

It is well recognized that the damage resistance of asphalt mixtures is significantly related to the properties of bituminous binders. Therefore, characterizing the mechanical properties of binders and improving them by means of modification has been a topic of intensive studies for many years [1-7]. Testing only binders is deemed to be much easier and cost effective than asphalt mixtures. However, the challenge is to find the most representative binder tests and parameters to describe the binder contribution to damage resistance. Identifying these tests and parameters would essentially and rationally guide the pavement engineers to optimise and select the most appropriate binder for a specific condition. Consequently, this would contribute to maximise the value of pavements and enhance their performance. There are many variables associated with the modification of bitumen (i.e. type of modifier, modifier content, and blending conditions). The selection of optimal combination of these variables should be based on specific properties of modified bitumens that can correlate well with the performance of pavement.

The dynamic shear rheometer (DSR) is usually used to characterise fundamentally the viscous and elastic properties of binders at wide range of temperatures. The DSR has also been used to apply repeated cyclic loading at specific loading and temperature condition until the specimen fails. The test provides continuous viscoelastic measurements which are used to assess the internal damage characteristic of materials during fatigue evolution [8-12]. This approach has been shown to provide an independent fatigue law regardless of loading mode and frequency when the fatigue analysis is based on the dissipated energy method. The healing potential of binders can also be evaluated by introducing short rest periods among the continuous loading sequence in fatigue test [13, 14].

Characterising the fracture properties, by means of essential work of fracture using the double-edged notched tension (DENT) test, has also been shown to be a promising approach for characterising the ductile fracture of bituminous binders [15-19].

In terms of rutting properties of binders, many rutting parameters have been developed to characterise the rutting resistance. SHRP parameter has been widely used to assess and grade the different binders based on the measured complex modulus and phase angle. The SHRP parameter has been increasingly criticized for the lack of correlation to pavement performance [8, 18, 20-23]. Other parameters including Shenoy parameter, Zero Shear Viscosity (ZSV) and creep compliance (Jnr) using the Multiple Stress Creep Recovery (MSCR) test, have been shown to provide more fundamental binder rheological evaluation that predict well the binder contribution to the rutting performance of pavement.

These fundamental analysis methods for characterising the fatigue and rutting properties of binders, are discussed and presented in this paper. A detailed description of the main elements associated with the DSR and Dynamic Mechanical Analysis (DMA) are also presented in this paper

2. Dynamic Shear Rheometer (DSR)

The dynamic shear rheometer is used to measure the viscoelastic response of materials when subjected to a given load state (degree and rate), and a given temperature. The load can be applied in a sinusoidal (oscillatory) mode, or in a creep and recovery mode. The sinusoidal load is normally applied under strain-controlled loading in which a small strain within the linear viscoelastic range is used and the resulting stress is measured. On the other hand, in the creep and recovery mode, a stress-controlled load is normally applied and the resulting strain is measured. The principal measurements taken by the DSR are the torque (*T*) and angular rotation (θ). The other mechanical properties are computed based on these measurements. Fig. 1 shows the main configuration of DSR testing. A sinusoidal load or creep load is applied to a sample of bitumen sandwiched between two parallel plates, and the amplitude of the transmitted torque and angular rotation of the sample, are measured.

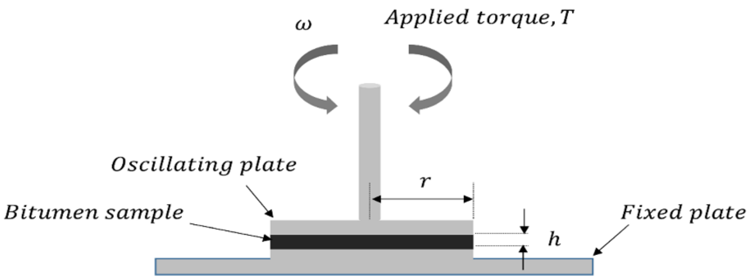

Fig. 1 The DSR testing configuration

The stress and strain are calculated based on the measured torque and angular rotation as follows:

$$\sigma = \frac{2\,T}{\pi\,r^3} \qquad (1)$$

Where:

σ = maximum shear stress (N/ mm2)

T = torque (N.m)

r = radius of the parallel plates (mm)

$$\gamma = \frac{\theta\,r}{h} \qquad (2)$$

Where:

γ = shear strain

θ = deflection angle (radians)

h = gap between parallel plates (mm)

The absolute complex modulus, G*, can be calculated from the following formula:

$$G^* = \frac{\sigma_{max}}{\gamma_{max}} \qquad (3)$$

It can be seen, from equations 1 and 2, that the magnitudes of the shear stress and strain are strongly dependent on the geometric properties of the oscillating plate, i.e. radius of the parallel plates and gap between the upper and the lower parallel plates. Therefore, various parallel plate sizes are used in the DSR testing depending on the expected stiffness of materials, to comply with the compliance of the device. Generally, the size of the plate decreases as the expected stiffness of the sample increases. Plates with smaller radius are normally used at lower testing temperatures while larger radius is used at higher testing temperatures to reliably measure the viscoelastic properties of the bitumen. A number of different parallel plate geometries are used in DSR testing to measure a wide range of bitumen stiffness. However, the following different plate sizes are suggested by SHRP-A-369 [24].

- Use 8-mm parallel plates with a 2-mm gap, for temperature range 0℃ to 40℃, when 0.1 MPa < G* < 30 MPa
- Use 25-mm parallel plates with a 1-mm gap, for temperature range 40℃ to 80℃, when 1.0 kPa < G* < 100 kPa.
- Use 40-mm parallel plates with a 1-mm gap, for temperatures > 80℃, when G* < 1 kPa

It should be mentioned that using 1 mm gap for some modified binders that contain undissolved particles, such crumb rubber, could give unreliable measurements because of the large volume of these particles. Thus, a larger gap size can be used when testing those binders [3]. As a rough practical rule, the gap setting should be set at least 3 times higher than the maximum dimension of any particle in the matrix [25].

2.1 Dynamic Mechanical Analysis (DMA)

The rheological properties of unmodified bitumen vary with the applied load rate and temperature, at temperatures below 60℃, and vary only with the temperature above 60℃, as illustrated in Fig. 2 [7]. In addition, the rheological properties of polymer modified bitumens are even more complicated where their mechanical properties vary with both temperature and shear rate at a temperature above 60℃. Therefore, the materials need to be characterised over a wide range of temperatures and loading times in order to predict their performance. In terms of DMA, a sinusoidal strain or stress controlled load, within the linear viscoelastic range, is applied to a sample of bitumen, in the DSR, sandwiched between two parallel plates with a loading frequency (rad/s)

The sinusoidally varying strain can be represented as in Equation 4 [7].

$\gamma_t = \gamma_o \sin \omega t$ *(4)*

where:

γ_t= dynamic oscillating shear strain

γ_o= peak shear strain

ω= angular frequency (rad/s)= $2 \pi f$, where f is the frequency Hz

t = the time (seconds)

The stress response is also sinusoidal but is out of phase by, δ, as represented in equation 5.

$\sigma_t = \sigma_o \sin(\omega t - \delta)$ *(5)*

where:

σ_t = dynamic oscillating shear stress, Pa

σ_o = peak stress, Pa

δ = phase angle, degrees

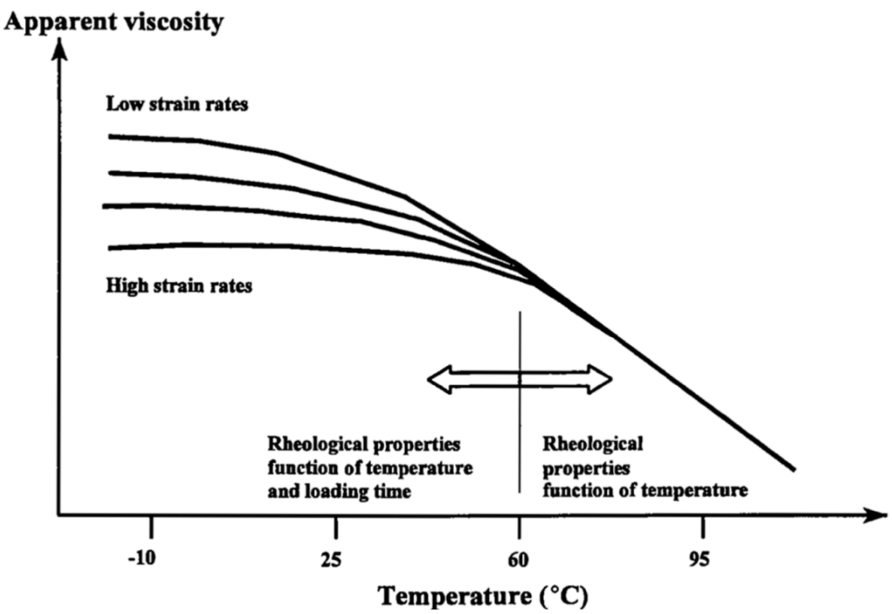

Fig. 2 Rheological behaviour of bitumen [7]

The phase angle, δ, is the phase or lag difference between the sinusoidal stress and strain, and it gives an indication of the viscoelasticity state of materials. For example, materials with 0°

phase angle, are purely elastic materials, where both the strain and stress waveforms are in the same phase, as can be seen in Fig. 3 (a); the deformation in this case is fully and immediately recovered after releasing the load if the load is below the yielding limit. On the other hand, materials with 90° phase angle, are purely viscous materials, as can be seen in Fig. 3 (c), the materials in this case approach an ideal liquid behaviour. For phase angles between 0° and 90°, the materials are viscoelastic and characterised by two components, namely storage component and loss component, as can be seen in Fig. 3 (b). In this case, the material response to the applied strain becomes highly dependent on loading time and temperature with a large amount of delayed elasticity [7].

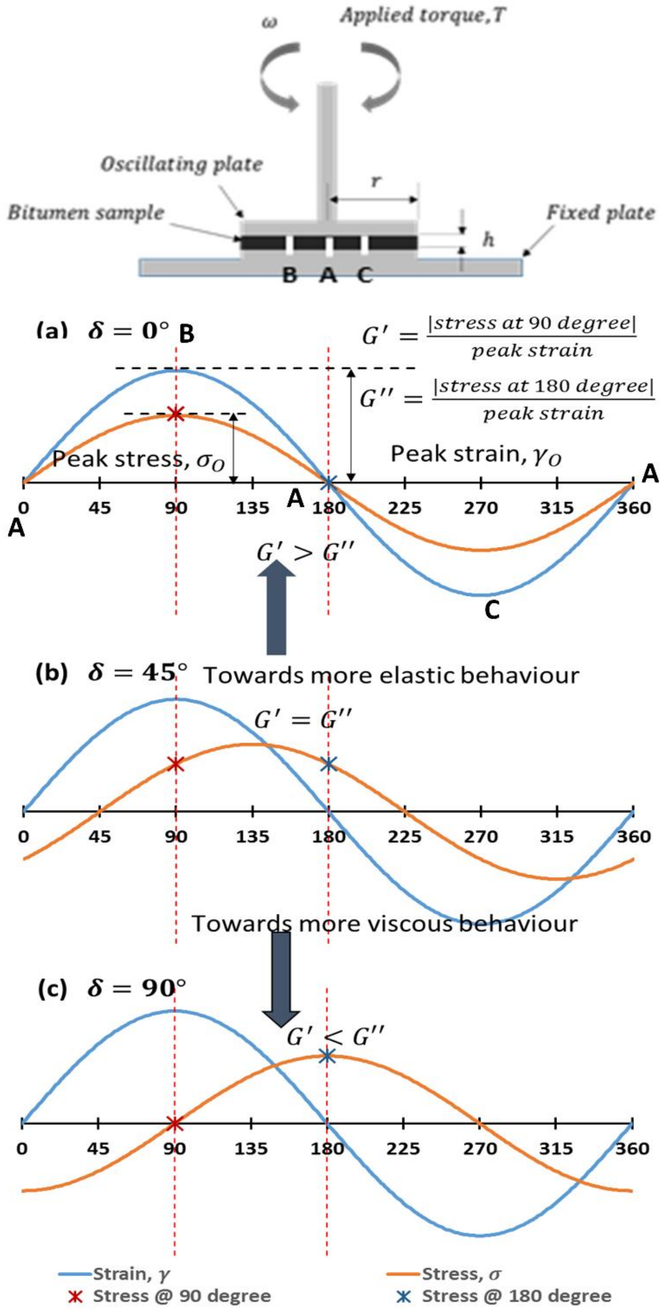

Fig. 3 Dynamic mechanical analysis representation

The resulting dynamic test outputs, for the stress and strain sinusoidal waveforms, are shown in Fig. 3 for the different viscoelastic states. The ratio of the resulting stress to the applied strain at any time is called the complex shear modulus, G*, defined by:

$$G_t = \frac{\sigma_t}{\gamma_t} = \left(\frac{\sigma_o}{\gamma_o}\right) \cos\delta + i \left(\frac{\sigma_o}{\gamma_o}\right) \sin\delta \qquad (6)$$

The term $\left(\frac{\sigma_o}{\gamma_o}\right)$ (the ratio of the peak stress to the peak strain) is called the norm of the complex modulus, $|G^*|$.

Equation 6 can also be written as:

$$G_t = G' + i\,G'' \qquad (7)$$

where:

G' is the storage modulus, and G'' is the loss modulus.

The storage modulus can be described in the following equation:

$$G' = |G^*| \cos\delta \qquad (8)$$

The storage modulus reflects the amount of energy that is stored and released elastically, including immediate and delayed elasticity, in each oscillation and it is also called the elastic component of the complex modulus [7].

The (shear) loss modulus is out-of-phase component or the imaginary part of the complex modulus. The loss modulus can be described in the following equation:

$$G'' = |G^*| \sin\delta \qquad (9)$$

The loss modulus is also referred as the viscous modulus or the viscous component of the complex modulus [7].

The magnitude of the norm of the complex modulus, |G*| can be calculated as the square root of the sum of the squares of the storage modulus and loss modulus as follows:

$$|G^*| = \sqrt{(G')^2 + (G'')^2} \qquad (10)$$

The ratio of the viscous component of the complex modulus to the elastic component of the complex modulus is known as the tangent of the phase angle or the loss tangent:

$$tan\,\delta = \frac{G''}{G'}\text{, thus}\quad \delta = tan^{-1}\frac{G''}{G'} \quad (11)$$

At low temperatures and high loading frequencies, the phase angle approaches 0°, the bituminous materials tend to behave like solid materials, and the storage modulus dominates over the loss modulus, as can be seen in Fig. 3 (a). On the other hand, at high temperatures and low loading frequencies, the phase angle δ approaches 90°, the bituminous materials tend to behave like liquids, and the loss modulus dominates over the storage modulus, as can be seen in Fig. 3 (c).

The dynamic viscoelastic response of the materials described above must be within the linear range during the DSR testing so that the stiffness of materials is not influenced by the magnitude of the applied strain or load, but it is only influenced by temperature and loading time. The linear viscoelastic region is identified using strain sweep tests as the point where the complex modulus decreases to 95% of its maximum value, as seen in Fig. 4, according to SHRP. This region varies with the measured stiffness of binders, the strain limit increases with a decrease in stiffness of the materials. Therefore, small strain boundaries must be used at low temperatures and increased at high temperatures. According to the SHRP research, the linear viscoelastic stress and strain limits, for neat bitumens, has been found to be a function of complex modulus according to the following notations:

$$\gamma = \frac{12.0}{(G^*)^{0.29}} \quad (12)$$

$$\sigma = 0.12\,(G^*)^{0.71} \quad (13)$$

where γ is the shear strain, σ the shear stress, Pa, and G* is the complex shear modulus. Fig. 5 shows the linearity strain limits plotted as a function of complex modulus, determined according to the 95% SHRP definition, for different neat and polymer modified bitumens tested at different temperatures and loading frequencies [26]. It can be seen from this figure that using a 1% strain level is assured to be within the LVE limits at a wide range of temperatures and loading frequencies. The figure also suggests that larger strain levels should be used when the binders are soft (low G*) at high temperatures and/or low frequencies; on the other hand, smaller strain levels should be used when the binders are hard (high G*) at low temperatures and/or high frequencies.

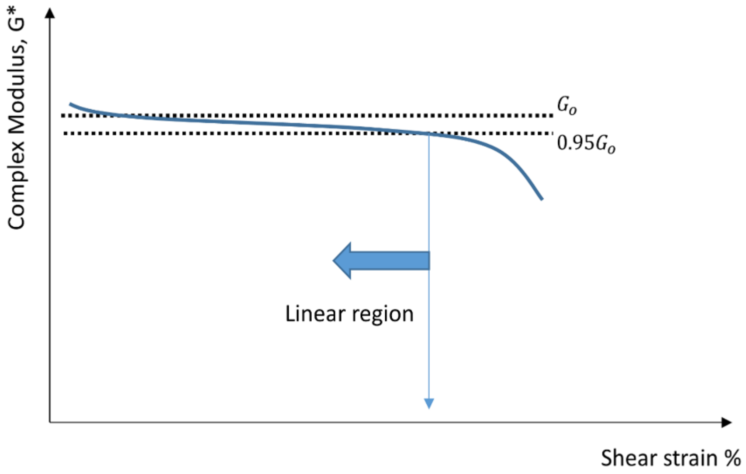

Fig. 4 Strain sweep to determine linear region

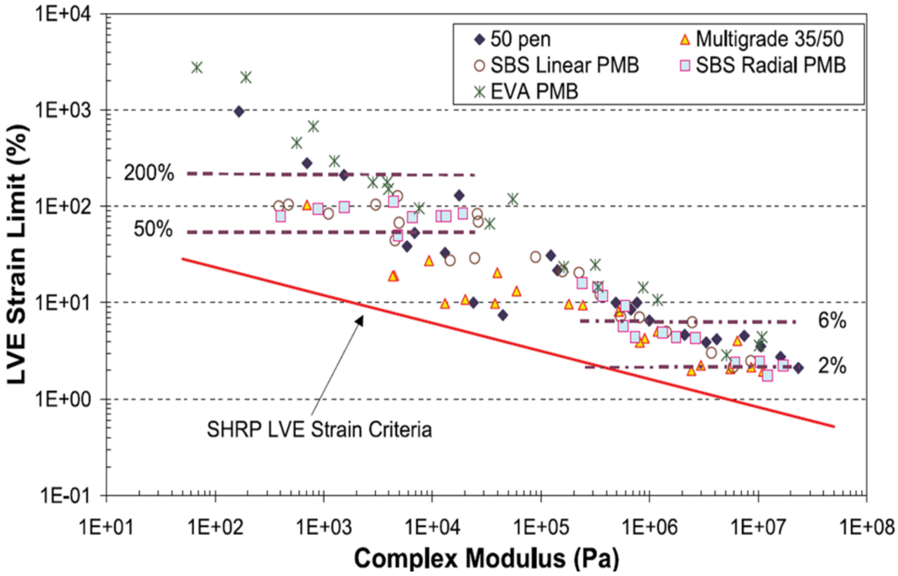

Fig. 5 Linear viscoelastic strain limits as a function of complex modulus [26]

2.2 Time-Temperature Superposition Principle (TTSP)

The TTSP is mainly used to represent the rheological properties of bituminous materials over a wide range of frequencies that exceed the compliance limit of the DSR. Studies conducted investigating the viscoelastic properties of binders have found that there is an interrelationship between temperature and loading time. The viscous response of bitumen is strongly dependent on temperature, while negligible effect for temperature is associated with the elastic behaviour; therefore, the influence of temperature and frequency can be separated using the time-temperature superposition principle [7]. The viscoelastic behaviour of binders at a given temperature over a defined range of loading times can be equivalent to the behaviour tested at different temperatures at the same loading time, through multiplying the loading times by a shift factor. Therefore, the viscoelastic measurements, i.e. complex modulus G* and phase angle tested at different temperatures, can be shifted to a reference temperature to produce a continuous curve at a reduced frequency or time scale, known as a master curve. This principle is also known as the time-temperature superposition principle or the method of reduced variables [7, 27]. Binders whose viscoelastic response over a range of temperatures and frequencies can be reduced to a smooth master curve are termed thermo-rheologically simple [7]. An example of the concept of applying the time-temperature superposition principle on a thermo-rheologically simple material, is shown graphically in Fig. 6.

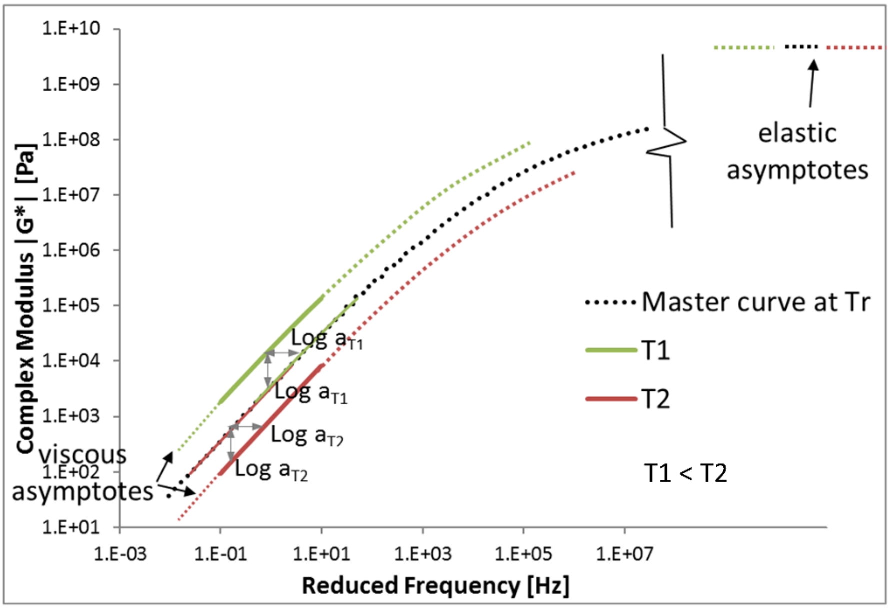

Fig. 6 Time-temperature superposition principle

Stiffness modulus of bitumen can approach a horizontal asymptote at low temperatures and at very high frequencies, as can be seen in Fig. 6. The elastic modulus of this asymptote is called the glassy modulus, G_g, and it is approximately independent of temperature and loading time. On the other hand, the stiffness modulus at high temperatures and low frequencies approaches viscous flow asymptotes with a unit slope. However, the viscous flow asymptotes at different temperatures are detached from each other but have the same unit slope. The binder is considered as thermo-rheologically simple when a change in temperature causes the modulus curve to shift together with its asymptotes over the same distance [7]. Thermo-rheologically simple behaviour is found in almost all unmodified bitumens; however, some types of modification and high wax content bitumens can alter significantly the behaviour of binders and make their viscoelastic behaviour more complex.

A master curve is constructed at a selected reference temperature by shifting horizontally other curves that are tested at different temperatures to coincide with the reference curve. This results in forming a single curve. Fig. 7 describes manually the shifting process in order to combine the curves into a smooth and continuous master curve. The horizontal shift factor, a_T, determined at each temperature is plotted versus temperature in conjunction with a master curve construction, as can be seen in Fig. 8

This curve provides a quick evaluation of the effect of temperature on viscoelastic properties of material. Several mathematical equations have been used to describe the relationship between a_T and temperature. The Williams, Landel and Ferry equation (WLF) and Arrhenius equation are the most widely used to model this relationship [7].

The extended frequency scale used in a master curve is referred to as the reduced frequency scale and defined as:

$$f_r = f \, . \, a_T \qquad (14)$$

where:

f_r = reduced frequency, Hz

f = original loading frequency, Hz

a_T = shift factor

For thermo-rheologically simple materials as in the most neat bitumens, the viscoelastic measurements such as complex modulus, G^*, the storage modulus, G', the loss modulus, $G''$and phase angle, δ, can all be shifted to obtain a master curve using the time-temperature superposition principle [7].

$$V\,(f, T) = V(f . a_T, T_r) \qquad (15)$$

Where:

V = viscoelastic measurements, i.e. G^*, G', G'' or δ

f = original loading frequency, Hz

T = Temperature, ℃

a_T = shift factor

T_r = reference temperature, °C

However, this approximation is not always valid for some modified bitumens or mastic as this shifting procedure does not give a unique master curve for other viscoelastic measurements such as the phase angle. In this case, the Partial Time-Temperature Superposition (PTTSP) introduced by Olard and Di Benedetto [28] can be used as an effective approximate for analysing the viscoelastic data [28-31]

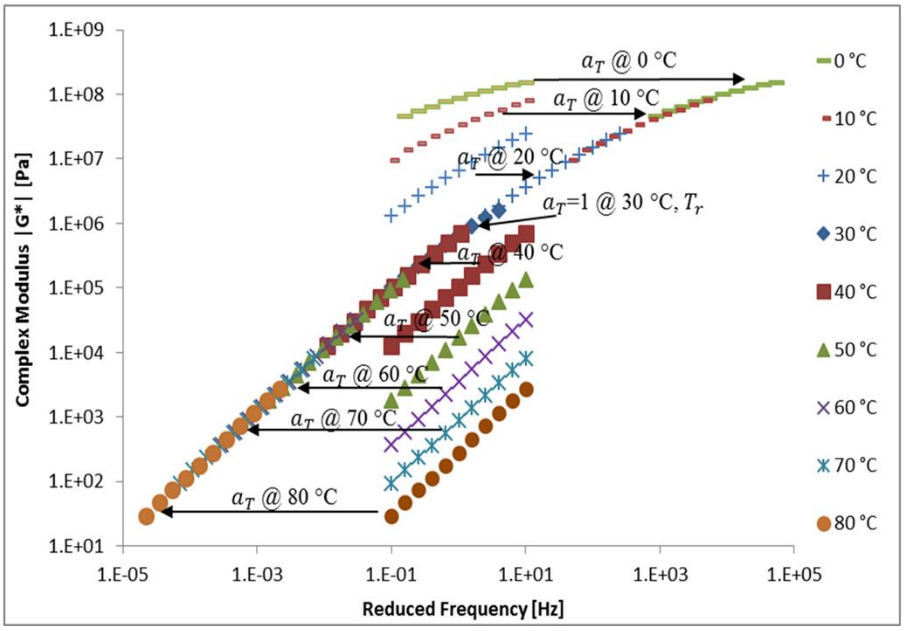

Fig. 7 Construction of the master curve for |G*|

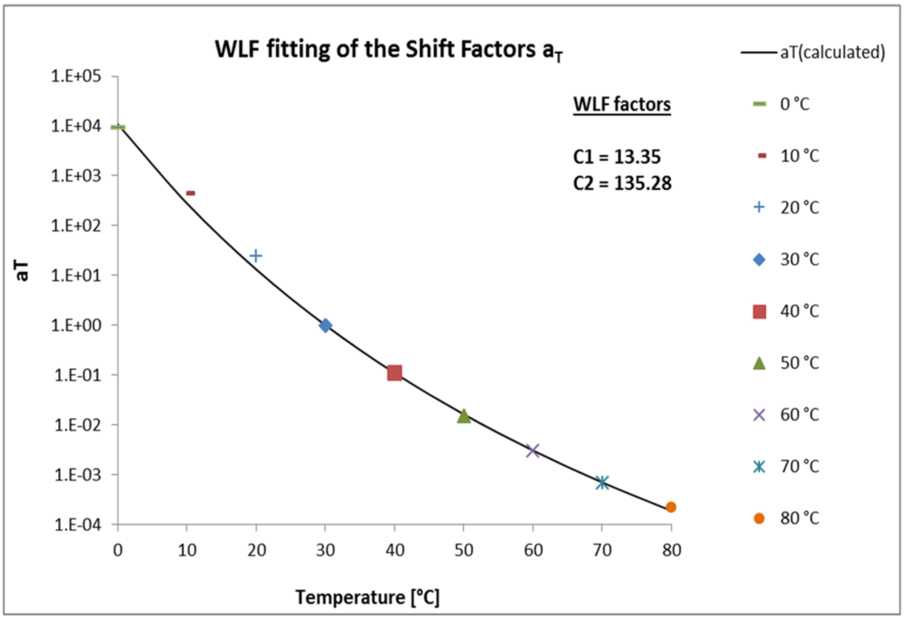

Fig. 8 a_T versus temperature plot

3. Binder Fatigue Testing

It is well recognised that fatigue resistance of asphalt mixtures is significantly related to the properties of their bituminous binders. Fatigue cracking usually starts and propagates within the binder or the mastic. Therefore, characterising the fatigue resistance of binders and improving this property by means of modification have been a topic of intensive studies for many years. The SHRP fatigue parameter ($G^* \sin \delta$) is widely used to characterise and control the fatigue property of binders within intermediate temperatures. Smaller ($G^* \sin \delta$) is desirable as the dissipated energy per loading cycle is reduced. Lower modulus G^* can better dissipate the work energy without developing large stresses, while lower δ (more elastic) helps the binders to regain their original shape with minimum dissipated energy. However, many studies have suggested that the current SHRP fatigue parameter does not necessarily reflect the true binder contribution related to mixture or pavement performance [8, 18, 20-23].

The reasons behind the poor binder-mixture correlation for the SHRP fatigue parameter are mainly attributed to:

(1) The fact that measuring G^* and δ under relatively small strain within the linear viscoelastic region does not represent the actual variety of strains or stresses that are taken place in binder films of pavements. This gives insufficient information about the response of binder films at other environmental and loading conditions.

(2) The current parameter does account for evaluation the strength of materials under damaging conditions since it considers applying only few loading cycles at a very low strain (1%). Indeed, binder films within the mixture undergo a wide range of strain distribution that can be up to 100 times of the bulk strains of the total mixture depending on the volumetric properties of mixtures and constituent material properties [32].

(3) The theoretical derivation behind the SHRP parameter is not clearly understood [22]. The assumptions used with this parameter neglect the effect of recoverable viscoelastic dissipation and also neglect the difference in cumulative maximum energy at failure among different binders that probably share the same value of $G{*} \sin \delta$. It should be mentioned that while the recoverable viscoelastic dissipation is very small for the unmodified bitumens, it cannot be neglected in the case of modified bitumens [33].

Consequently, many different approaches have been investigated to develop a more fundamental and related performance-based characterisation [8, 18, 34]. Time sweep repeated cyclic loading (TSRCL) test using the DSR have been successfully used to evaluate the fatigue properties of binders [8, 20, 35]. Applying the dissipated energy approach to analysing the fatigue data of TSRCL test has been shown to provide more fundamental material properties and an intrinsic fatigue law [20, 34, 36].

Moreover, another accelerated fatigue test named the linear amplitude sweep (LAS) test has been recently proposed by Hintz, at el. [37]. The method was developed based on using viscoelastic continuum damage (VECD) and fundamentally linked to the TSRCL test [37]. The test is considered a performance related one and can be conducted in short period of time; however, the fatigue life equation is derived after several complex mathematical formulations and statistical fitting. Additionally, the conceptual assumption of evaluating the material integrity under accumulated damage, which is based on the reduction in $G^* \sin \delta$, can be negated by a non-linear decrease.

The DSR can also be used to measure the fracture energy of binders by applying a monotonic load at constant shear rate. This test is known as the Binder Yield Energy Test (BYET) and provided fundamental parameters that can be used to predict the fatigue cracking [38]. One parameter called critical strain energy density (CSED) is calculated from the area under the stress– strain curve until the maximum stress. Other one is the strain that corresponds to the maximum stress. These parameters have shown to provide a good correlation with fatigue performance based on results from the FHWA Accelerated Loading Facility [38].

Fatigue behaviour of binders has also been evaluated based on the delayed elastic response of binders tested empirically using a ductility test machine or fundamentally by the multiple stress creep recovery (MSCR) test using the DSR [18].

It is believed that the main drawback of the SHRP fatigue parameter is the neglect of the damaging circumstances that would take place in the pavement during the fracture process [17, 39]. These damaging conditions are normally accompanied by high strain levels and yielding in binder films in the nonlinear viscoelastic range. In response to that, researchers at Queen's University proposed the double-edged notched tension (DENT) test which is based on the concept of essential work of fracture (EWF) of materials in a ductile state [39]. The binder ranking based on this method showed a strong correlation with observed fatigue cracking in the accelerated loading facility (ALF) and exactly the same ranking as the push-pull asphalt mix fatigue test [18, 19]. More details about the dissipated energy approach and the concept of essential work of fracture (EWF) and DENT test are presented in the next sections.

3.1 Dissipated energy approach

Several research studies have supported the use of the dissipated energy approach for fatigue damage analysis. This approach enables an independent fatigue law to be derived regardless of loading mode, frequency, rest periods and temperature [34, 40, 41]. When viscoelastic materials are subjected to cyclic loading, they generate different paths for the loading and unloading cycles leading to hysteresis loops. The dissipated energy per cycle is computed as the area within the hysteresis loop and calculated by the following equation:

$$w_i = \pi \, \sigma_i \, \varepsilon_i \, sin \, \delta_i \qquad (16)$$

where w_i = the dissipated energy at cycle i; σ_i, ε_i, δ_i = the stress amplitude, strain amplitude and phase angle at cycle i, respectively. It can be seen that this approach contains the main viscoelastic parameters (stress, strain and phase angle) and thus monitoring the variation in these parameters during the fatigue evolution allows an intrinsic fatigue law to be derived. The early studies of applying the dissipated energy approach to characterise fatigue cracking in asphalt mixtures were introduced by Van Dijk and his colleagues [40, 42, 43]. They showed that the relation between accumulated dissipated energy (W_{fat}) at failure and number of cycles N_f to failure depends solely on material properties and it is constant irrespective of the mode of loading, frequency and temperature. The accumulated dissipated energy after n cycles can be calculated as:

$$W_n = \sum_{i=0}^{n} w_i \qquad (17)$$

The relationship between cumulative dissipated energy and the number of load cycles to failure was found to be a power law relation as follows:

$$W_{fat} = A. N_{fat}^{z} \qquad (18)$$

where W_{fat} = total dissipated energy until failure due to fatigue cracking, N_{fat} = number of loading cycles to fatigue; and $A \; and \; z$ = material constants. The main concern about this approach is that the sum of dissipated energy includes energies that are not responsible for fatigue damage such as recoverable viscoelastic energy and heat energy. Therefore, Ghuzlan and Carpenter [41] proposed the use of the Dissipated Energy Ratio (DER) to study the fatigue behaviour. The DER or the Ratio of Dissipated Energy Change (RDEC) approach was then developed by Carpenter and Shen [44] who emphasised the fact that damage will only be generated when there is a difference in dissipated energy between consecutive cycles. RDEC is expressed as:

$$For\ controlled\ stress\ mode: RDEC_i = \frac{(w_i - w_j)}{w_i.(i-j)} \qquad (19)$$

$$For\ controlled\ strain\ mode: RDEC_i = \frac{(w_j - w_i)}{w_i.(i-j)} \qquad (20)$$

where $RDEC_i$ = ratio of dissipated energy change value at cycle i; w_i and w_j = dissipated energies at cycles i and j; and i, j = loading cycle, $i > j$. The subtraction, in the numerator of Equations 19 and 20, between consecutive cycles is believed to eliminate energies like viscoelastic damping, plastic deformation energy and thermal energies that are not causing damage while keeping the relative amount of incremental damage coming from each additional load cycle [13, 34, 45]. As previously depicted by Ghuzlan and Carpenter [41] and Shen, Chiu and Huang [13], three distinct phases can be identified when the RDEC is plotted versus the number of cycles, as shown in Fig. 9.

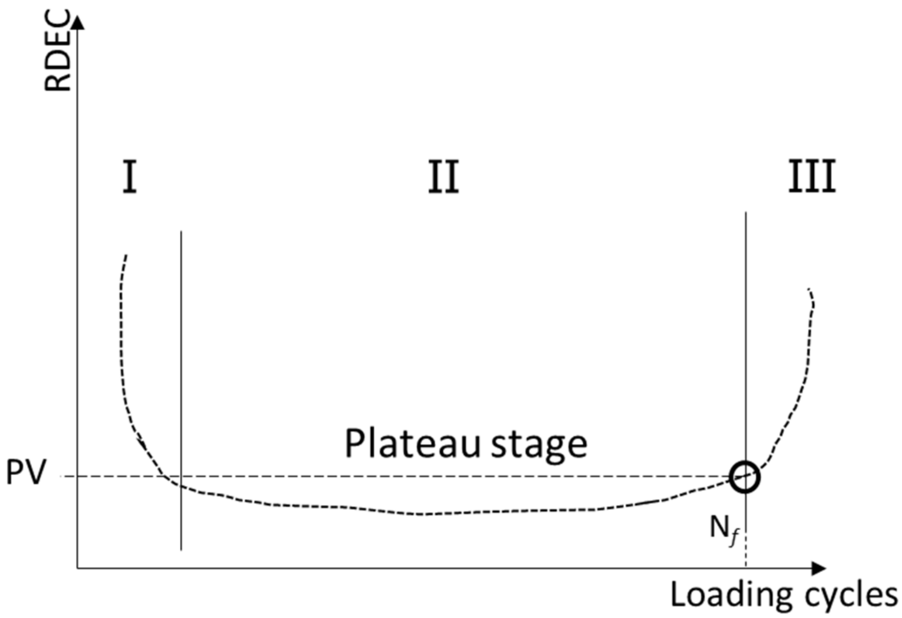

Fig. 9 Typical RDEC plot versus load cycles

Phase I is defined by a rapid decrease of the RDEC. The decrease is considered to be not only caused by fatigue damage but includes molecular reorientation and other reversible phenomena such as thixotropy. Phase II reflects the internal damage characteristic of materials and is defined by a plateau of steady-state micro-crack development. The change in the dissipated energy is almost constant with a relatively constant percentage of input energy being transformed into damage. Phase III is defined by a rapid increase in RDEC and thus indicates a sign of fatigue failure. Carpenter and Shen [44] proposed that the RDEC value at Phase II or the plateau value (PV) is insensitive to the mode of loading. Several studies showed that PV can provide a unique relationship with the number of loading cycles to failure for different mixtures, loading modes and loading levels [13, 34, 36, 44].

The relationship between PV and the number of load cycles to failure was found to be a power law relation as follows [40]:

$$PV = C.N_{fat}^{d} \qquad (21)$$

where c and d = regression constants; and N_{fat}= number of load cycles to failure.

3.2 Definition of fatigue failure

Under repeated cyclic loading, the fatigue life should correspond to the transition point between crack initiation and crack propagation. Several approaches have been adopted to correctly identify the fatigue failure point [46-48]. The classical approach of a 50% decrease in the initial stiffness is the most commonly used approach to identify fatigue failure in bituminous materials. However, many studies have shown that this criterion may not always be appropriate for analysing fatigue properties [20, 47, 48]. The reduction in G* is sometime attributed to other artefact effects such as heating and thixotropy and not only by fatigue [49]. Additionally, some modified binders, especially the highly polymer modified ones, can allow larger strains to be sustained before the material is failed and thus larger continuous decrease in stiffness (more than 50%) would still be within the fatigue life-span [50, 51]. Also, the different stress/strain loading modes do not always produce a unique intrinsic fatigue law if this arbitrary definition is applied. Therefore, it is important to find other approaches that are not arbitrary but can define fatigue failure based on a more fundamental analysis. The Dissipated Energy Ratio (DER) concept proposed by Pronk and Hopman [52] was shown to provide a reasonable criterion for defining the fatigue failure of bituminous mixtures.

$$DER = \frac{\sum_{i=1}^{n} w_i}{w_n} \qquad (22)$$

where, w_i= dissipated energy per cycle, w_n= dissipated energy at cycle n. The plotting of the relationship between DER and number of cycles in the stress-controlled mode provides a distinctive way to evaluate the stage of fatigue damage at which the material undergoes a transition from crack initiation to crack propagation. Fig. 10 (a) shows the evolution between DER and loading cycles, where during the first portion there is negligible damage of the materials and DER = n, i.e. the dissipated energy is almost equal for consecutive cycles. As the relative difference in dissipated energy between consecutive cycles becomes significant, DER starts deviating from the equality line which is interpreted as crack initiation. The fatigue failure N_f point in Fig. 10 (a) is defined by the sudden change in DER which can be related to the point of transition from crack initiation to crack propagation. This change is considered to be highly material specific and independent of the mode of loading [20, 46]. Under strain controlled testing the N_f is defined by the intersection of two tangents as shown in Fig. 10 (b).

Another fatigue failure criterion was evaluated from the evolution of phase angle versus complex modulus (Black diagram), see Figure 10 (c). Di Benedetto et al. [53] demonstrated that using the Black diagram during fatigue evolution is a promising approach to defining the stages of fatigue development. The change in the process evolution of the Black diagram in Fig. 10 gives a definitive limit between crack initiation and crack propagation. The N_f value can be defined from the value of the phase angle at the intersection of two straight lines. These lines are used to linearize the evolution of phase angle for each period; N_f corresponding to the defined phase angle is then determined.

In terms of continuum damage mechanics, fatigue damage commences with homogeneous global damage which is distributed in the body of the material. The microstructural state of the material during this stage is reflected by a steady change in the stress-strain relationships (stiffness modulus, phase angle, dissipated energy…etc.). On the other hand, a rapid change in the mechanical properties of materials happens corresponding to the occurrence of coalescence and unstable propagation of cracking by means of molecular rupture and molecular scission leading to structural failure. Thus, unlike the phenomenological approach of 50% decrease in the initial stiffness, the DER and the Black diagram can be considered a mechanistic-based approach as they account for the evolution of damage mechanics based on monitoring the main viscoelastic measurements (G* and phase angle) throughout the fatigue process.

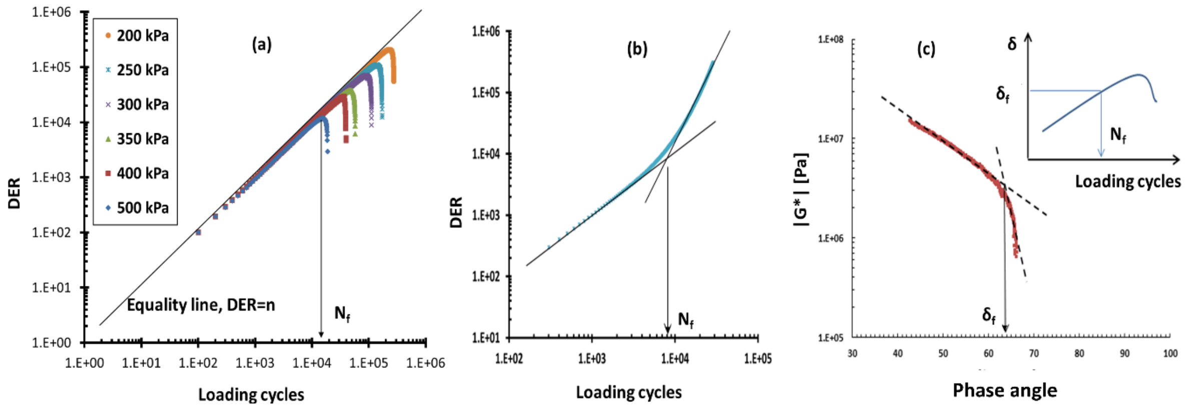

Fig. 10 Identifying Nf (a) from the DER vs. number of load cycles under controlled stress loading conditions, (b) from the DER vs. number of load cycles under controlled strain loading conditions and (c) from the evolution of phase angle versus complex modulus (Black diagram)

3.3 Essential work of fracture (EWF) method

The EWF concept has been increasingly used to determine the fracture toughness in polymers. Yet, there are only few studies that have used this test on bituminous materials. Andriescu et al. [39] successfully applied this test on bituminous binders. They found that no correlation exists between fracture properties and the SHRP fatigue parameter. That means binders with desirable fatigue properties, according to (G* sin δ), do not necessarily have good fracture properties and vice versa. Therefore, it is important to characterise the fracture behaviour of materials for a proper material selection.

According to the EWF test when a notched ductile specimen (binder or bituminous mixture) is being loaded the total energy required for fracturing consists of two separate parts; an essential work takes place in the inner process zone of the progressing crack, and nonessential or plastic work performed in the outer plastic zone [54], as shown in Fig. 11 (b). The essential work is the energy dissipated in the fracture region that is needed to create two new fracture surfaces and it is considered a constant material property [54]. The nonessential or plastic work is the energy dissipated in ductility, plasticity, and tearing. The essential work of fracture is proportional to the ligament cross-sectional area, whereas, the plastic work is related to the plastic zone volume multiplied by a constant that represents the shape of the plastic zone.

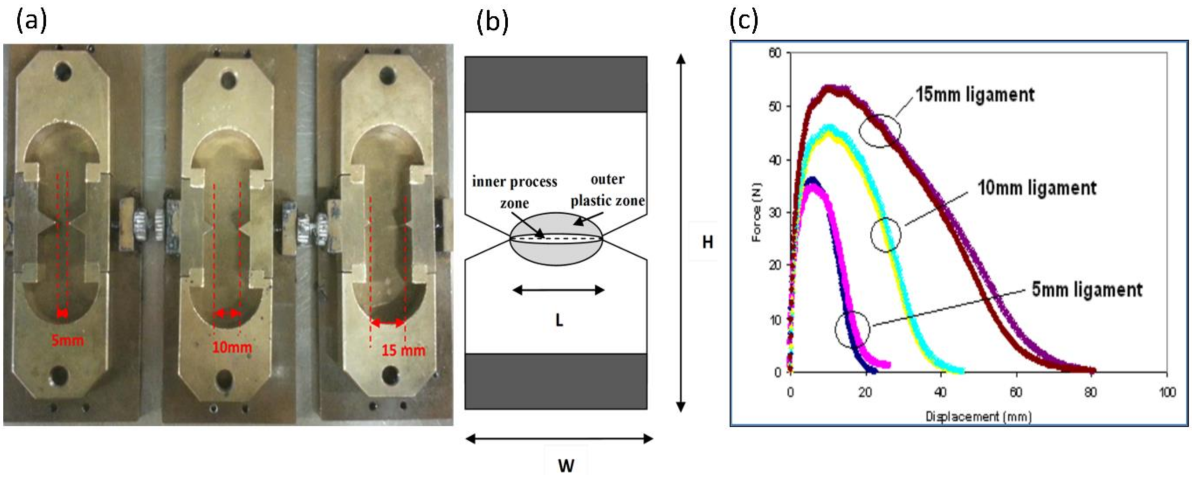

Fig. 11(a) DENT test moulds; (b) Schematic representation of inner and outer zone for a typical DENT specimen; (c) Typical raw data from DENT test

The total work of fracture (W_T) is expressed mathematically by the following simple relationship:

$$W_T = w_e \,.\, l.B + \beta.w_p.l^2.B \qquad (23)$$

The above equation can be written in specific terms by dividing both sides by ligament cross-sectional area (lxB) as follows:

$$w_t = {W_T}/{l.B} = w_e + \beta.w_p.l \qquad (24)$$

where: W_T is the total work of fracture in a DENT test as provided by the area under the force-displacement curve (J), as can be seen in Fig. 11 (c), w_t is the total specific work of fracture (J/m^2), l is the ligament length (m), B is the sample thickness (m), β is a geometrical constant which depends on the shape of the plastic zone, w_e is the specific essential work of fracture (J/m^2), and w_p is the specific plastic work of fracture (J/m^3) [39, 54].

The test is performed on similar specimens with different ligament lengths (5, 10, and 15 mm) as shown in Fig. 11 (a), the total work of fracture W_T is obtained by measuring the area under the force-displacement curve (J). The total specific work of fracture is then calculated by dividing the latter by ligament cross-sectional area (lxB).

By plotting the w_t versus the ligament length and using a linear fitting procedure, a straight line results as shown in Fig. 12. The intercept of the line represents the specific essential work (w_e) and it is attained by extrapolation to zero ligament. While the slope of the line represents the plastic work of fracture, multiplied by the geometry constant β. The references in the literature that deal with EWF suggest many assumptions and conditions that need to be met in order to have an intrinsic material property [39, 55, 56]. These recommendations, conditions and assumptions are as follows:

- The ligament must be fully yielded before cracking initiates.
- Load–displacement diagrams should be self-similar in appearance for all ligament lengths, verifying a common geometry of fracture.
- The sample must be yielded under a plane stress state of tension.

Generally, the first two requirements are easily fulfilled; however, the third assumption is not always attained. Pure plane stress prevails over plane strain in thin sections (small thickness to ligament ratio) and its influence gradually decreases as the ligament length reduces for a given thickness. The influence of thickness on the fracture toughness is illustrated in Fig. 13 [57]. It can be seen from Fig. 13 that when the thickness reaches a certain value B_c, pure plane strain conditions are taken place and the fracture toughness becomes independent of thickness. Also, there is an optimum thickness, B_o, at which the plane stress conditions are met. In the transition zone between B_o and B_c, the fracture toughness is at plane-stress/plane-strain (mixed mode). The thickness boundaries B_o and B_c may be estimated as follows:

$$B_o = \frac{K_{1c}^2}{3\pi\sigma_y^2} \quad (25)$$

$$B_c = 2.5\left(\frac{K_{c1}}{\sigma_y}\right)^2 \quad (26)$$

Where K_{c1} is the fracture toughness, and σ_y is the tensile yield stress of material.

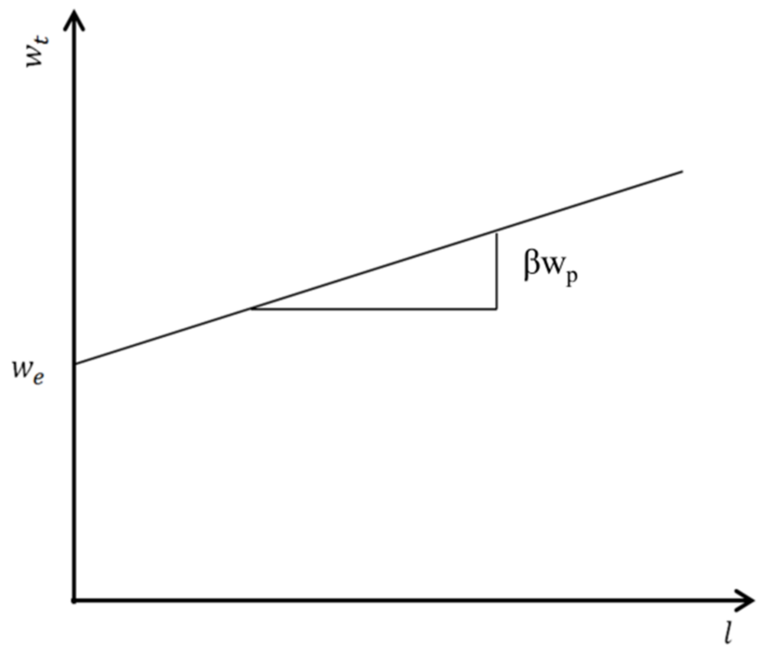

Fig. 12 Schematic sketch illustrating the relationship between w_t and ligament length l

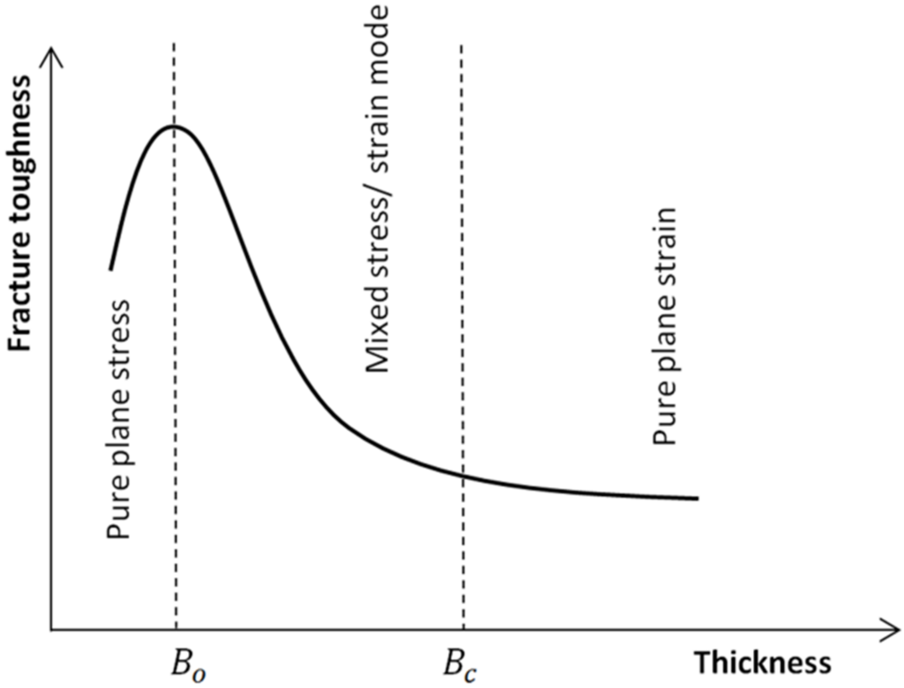

Fig. 13 Schematic sketch illustrating the influence of thickness on the fracture toughness

To examine the plane stress or strain conditions, the Hill criterion can be applied [58]. According to that when a plot is made between the net section stress (maximum load divided by ligament cross section), σ_n, versus ligament length, L, a horizontal line should appear with $\sigma_n = 1.15\ \sigma_y$, where σ_y is the yield stress of the material. However, these conditions are not normally met in the case of bituminous binders. Bituminous materials are not as tough as polymers or metals, and having very thin samples to maintain plane stress is not achievable from a practical point of view. Therefore, the from mixed plane stress/ plane strain normally occurs in the case of bituminous binders. It should be noted that the plane strain value of w_e is also considered a valuable material property that is independent of sample geometry [39, 54].

The specific work of fracture in Equation 24 represents the energy required for full ligament yielding preceding the necking and tearing. However, research groups that deal with fracture of polymers have introduced the concept of energy partitioning by splitting the total energy of the load-displacement curves in the two energies [56]:

a) the specific work of fracture required for yielding (w_y) and
b) the specific work of fracture required for necking plus tearing (w_{n+t})

Theoretically, the full ligament yielding occurs prior to crack initiation, however, the onset of crack initiation is normally superposed with yielding [56]. It is believed that the load drop at full ligament yielding in the load-displacement curve corresponds to a clear transition between crack initiation and the onset of crack propagation [59, 60]. The "necking" and "tearing" stage take place after the load starts dropping and that accompanies with a reduction in ligament cross-section and crack-tip blunting. The mathematical terms of Equation 24 after applying the partitioning concept becomes as follows:

$$w_t = w_{t(yielding)} + w_{t(necking+tearing)}$$

$$= (w_{ey} + \beta_y . w_{py} . l) + (w_{en} + \beta_n . w_{pn} . l) \qquad (27)$$

Researchers on polymers have shown that the energy partitioning presented above may be a good technique to overcome problems related to plane stress/ plane strain conditions and also to have more information about fracture parameters related to crack initiation and crack propagation [56, 60]. It is interesting to consider applying the partitioning concept to bituminous binders. Indeed, Subhy et al. [61] successfully used this concept to evaluate different neat bitumens and different rubberised bitumens so that the effect of plane stress/strain conditions can be reduced. The study has shown that the separation of fracture initiation resistance and fracture propagation resistance could give different materials ranking.

Finally, an approximation of the critical crack opening displacement CTOD can also be defined from the ratio of over the net section stress. It is believed that a sufficient and complete yielding in the ligament section takes place at the smallest ligament, thus CTOD is approximated as $\delta_t = w_e/\sigma_{net}$ [57]. CTOD gives an indication about the strain tolerance of the binder in the presence of a crack and a high degree of stress concentration during the ductile regime. It is a useful parameter, and has a very good correlation with the fatigue property where binders with large CTOD is deemed to have higher fatigue cracking resistance. It was also successfully used to rank the fatigue performance of binders at different temperatures and rates of loading that cover the ductile state, and it is highly recommended by many researchers for performance grading of both binders and mixture [18, 19, 39, 62].

4. Binder Rutting Testing

Accumulation of permanent deformation in a flexible pavement occurs at high in-service temperatures and/or under slow moving loads. The densification and shear viscous flow are the main mechanisms that are associated with rutting at varying degrees [63, 64]. Densification can be controlled and minimised by the mix volumetric properties while the shear plastic deformation is related to the viscoelastic properties of binders and the bonding interaction between bitumen and aggregate. It is well recognised that the viscous component of binder dominates the rheological response at high temperatures and extended loading time and it is, therefore, solely responsible for the non-recoverable deformation [27]. Many high temperature parameters and test methods have been developed to characterise the rutting resistance of binders [19, 65, 66]. The following test methods and parameters are the most frequently used to predict the high-temperature performance of binders.

4.1 Superpave high-temperature parameter (G/sin δ)*

The current Superpave high-temperature binder parameter is specified such that the binder after ageing in the RTFOT must be greater than 2.2 kPa and 1.0 kPa for unaged binder at the maximum 7-day average pavement design temperature [67]. This parameter is derived from the definition of the loss compliance (J"= sinδ/G*) [68]. It is, therefore, important to select binder with reduced (J") to minimise the nonrecovered strains (γ_{nr}) where:

$$\gamma_{nr} = \sigma_o \, {}^{\sin\delta}/_{G^*} \qquad (28)$$

There have been considerable criticisms of the Superpave parameter (G*/sinδ) because of the lack of correlation with asphalt mixture or pavement performance [65, 66, 68]. Also, the lower contribution of the elasticity parameter, δ, underestimates the benefits that are obtained by elastomeric modifiers. Moreover, this parameter is derived by testing binders within the linear viscoelastic region at a fixed temperature and frequency. It is measured at (ω=10 rad/s) and at this frequency the delayed elasticity cannot be neglected [69]. Consequently, many test methods or refinements have been proposed to develop a parameter that is more sensitive and related to pavement performance [66, 68].

4.2 Shenoy rutting parameter

Shenoy [68] proposed (G*/(1-(1/tanδ sinδ)) as a refinement to (G*/sinδ). The parameter was derived through a semi-empirical approach. It represents the inverse of the non-recoverable compliance and is derived by linking the strain response in the creep experiment with the complex modulus G* from oscillatory shear experiments at a matched timescale. This parameter is more sensitive to phase angle than the Superpave parameter; therefore, it better explains the changes in elastic properties when adding the polymeric modifier. It should be noted that the term (1-(1/tanδ sinδ) becomes zero when δ is equal to or lower than 52 degrees; therefore, the parameter is not applicable at values of δ below 52 degrees. However, if it happens that δ gets lower than 52 degrees, the parameter, $G^*/(\sin\delta)^9$, can be used to give a very close approximation to the original parameter G*/(1-(1/tanδ sinδ) based on the best-fit curve [68]. The temperature at which G*/(1-(1/tanδ sinδ) is greater than (50 Pa) for RTFO aged binders at ω=0.25 rad/s, has been specified as the high specification temperature T_{HS} (℃) [70].

4.3 Zero Shear Viscosity ZSV

Zero shear viscosity is defined as a measure of viscosity at a steady state flow when the shear rate approaches zero, and it is a physical property of the material that is independent of shear rates and stress. The ZSV concept is based on the fact that the purely dissipative viscous component is solely responsible for the non-recoverable deformation [71]. Zero shear viscosity is strongly related to rutting resistance of bituminous materials and many studies showed that ZSV of binders has a strong correlation to rutting performance [72, 73]. The ZSV is highly influenced by the higher molecular weight fraction and binder stiffness, and thus, it can reliably predict the rutting resistance of binders under slow-moving load [72].

Even though ZSV is an intrinsic property of bitumen, a ‘true’ value of ZSV may never be achieved particularly for highly modified bitumen. Several factors undermine obtaining a reliable measurement for ZSV; amongst them are, the extrapolation and approximations that are made to calculate the ZSV, the different test methods and experiments used, and the fact that a steady state flow is not readily reached for some highly elastomer modified bitumens.

Generally, ZSV can be identified from three test methods; single creep tests, creep and recovery and oscillation tests [69]. The oscillation test has been considered in this paper. Utilising a cyclic oscillatory test in the low-frequency domain has been suggested by many researchers to evaluate ZSV [69, 72, 74, 75]. In this method, a frequency sweep test within the linear viscoelastic regime at a specific high test temperature is used to determine the ZSV [76]. At low frequencies and relatively high temperatures, binders tend to behave like Newtonian fluids in which the complex viscosity becomes independent of the applied shear rate or frequency. Additionally, the contribution of the delayed elasticity or recovered deformation is minimised and approaches zero as frequency approaches zero, hence, the total dissipated energy reflects only the viscous component or permanent deformation. Therefore, ZSV better characterises binders than the SHRP parameter G*/sin δ at 10 rad/s, because the latter does not distinguish between the effects of recovered and non-recovered strain on the total dissipated energy [69]. ZSV can be defined as the ratio between the complex modulus G* or loss modulus and the radial frequency as the frequency approaches zero [74, 75].

$$\omega \rightarrow 0 \;\Rightarrow\; \eta^* \; or \; ZSV \;\rightarrow\; \frac{G^*}{\omega} \;\; or \;\; \frac{G''}{\omega} \qquad (29)$$

In the case of neat binder, the effect of the delayed elasticity is substantially diminished at low frequencies and high temperatures, and a plateau is evident when a curve is plotted of complex viscosity versus frequency. Thus, ZSV can be readily identified by the asymptote. However, for highly modified bitumen such as high content crumb rubber modified bitumens or cross-linked polymer bitumens, such a plateau is not always developed as shown in Fig. 14.

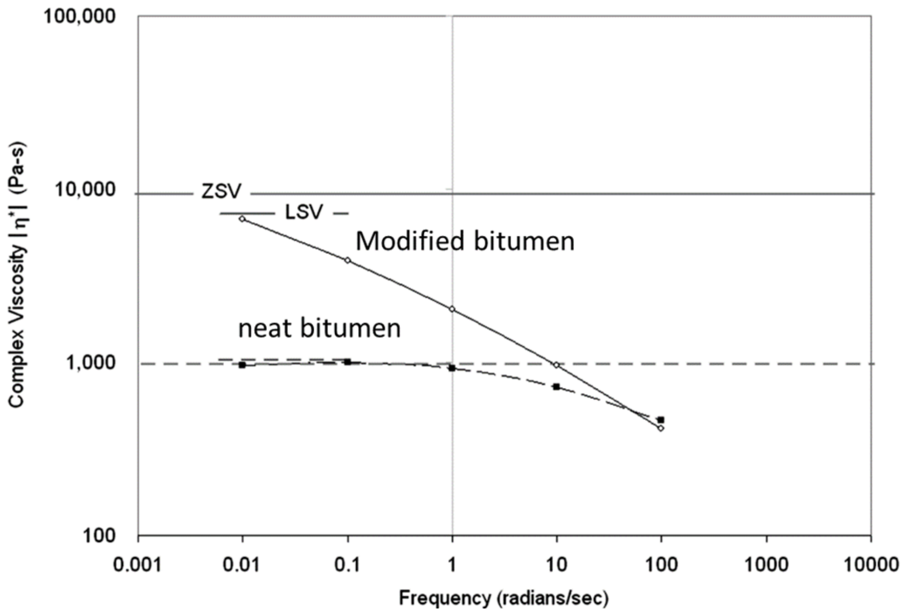

Fig. 14 Complex viscosity versus frequency [19]

Since it is not possible to measure directly the complex viscosity at very low frequencies due to the limitations of DSR resolution, mathematical models are usually used to fit the data and extrapolate the complex viscosity to very low or zero frequency [69]. The flow curve of pseudoplastic fluids can be adequately fitted by using a four parameter Cross model as follows [74, 75]:

$$\eta^* = \frac{\eta_0 - \eta_\infty}{1 + (K\omega)^m} + \eta_\infty \qquad (30)$$

Where η^* is complex viscosity, η_0 is zero shear viscosity (first Newtonian region viscosity), η_∞ is infinite shear viscosity in the second Newtonian region viscosity (viscosity at infinite frequency, ω is frequency (rad/s), K and m, are constants.

The Cross model can also be simplified to three parameters as shown in Equation 31 because the infinite viscosity is too small in comparison to complex viscosity and zero shear viscosity ; therefore, it can be neglected [74]:

$$\eta^* = \frac{\eta_0}{1+ (K\omega)^m} \qquad (31)$$

The Carreau model is also used to fit the measurements of viscosity of bituminous binders. It has been revealed that different ZSV results can be obtained from using Carreau and Cross for the same test data [77].

$$\eta^* = \frac{\eta_0 - \eta_\infty}{[1+ (K\omega)^2]^m} + \eta_\infty \qquad (32)$$

The main difference between the two models is that the curve is artificially forced by the fitting parameters of Carreau model to generate a plateau at low frequencies, leading to a more noticeable curvature than with the Cross model, resulting in a smaller ZSV [77].

Also, some modified bitumens experience very high complex viscosity gradients at low frequencies, the ZSV values become unreliable from the rheological point of view [72]. Thus, low shear LSV viscosity is sometimes suggested to solve this problem. It was also shown that complex viscosity measured at 0.001 and 0.01 Hz give as a good correlation with mixture rutting performance as those measured at 0.0001 Hz [72].

4.4 Multiple Stress Creep and Recovery (MSCR)

It is well recognised that the nonrecovered deformation of binders has a significant influence on pavement rutting performance. The multiple stress creep-recovery (MSCR) test was firstly developed by the NCHRP 9-10 research program [20] and then extended by Dongré et al. [78]. The validity of the test to characterise binders at high-temperature has been ascertained by many researchers [79-82]. The MSCR test consists of applying repeated creep and recovery of shear stress for a short duration of 1s and then removing the stress for 9s to allow the material to recover, this is repeated for 10 cycles using different stress levels. The creep stress levels start at 25 Pa and end at 25600 Pa by doubling the stress each time. The test is usually performed on RTFOT aged samples to simulate the ageing during mixing and construction. The test is conducted on samples between two parallel plates of 25mm diameter using the dynamic shear rheometer (DSR) equipment and described in detail in the ASTM D7405-08 or AASHTO TP 70-12 standards. In the new test protocol, two levels of shear stress are used, 100 Pa and 3200 Pa, 10 repeated cycles of 1s creep and 9s recovery are applied at each stress level with no time lag between cycles. A typical one cycle of creep-recovery is shown in Fig. 15; the parameters retrieved from MSCR test are:

$$Recovery\,\%\ at\ 100\ Pa\ or\ 3200\ Pa = \frac{1}{10}\left\{\sum_{i=1}^{10} \frac{\gamma_{(r)i}}{\gamma_{(t)i}}\right\} * 100 \qquad (33)$$

$$J_{nr\ at\ 100Pa}\ \left(1/_{KPa}\right) = \frac{1}{10}\left\{\sum_{i=1}^{10}\frac{\gamma_{(nr)i}}{0.1}\right\} \qquad (34)$$

$$J_{nr\ at\ 3200\ Pa}\ \left(1/_{KPa}\right) = \frac{1}{10}\left\{\sum_{i=1}^{10}\frac{\gamma_{(nr)i}}{3.2}\right\} \qquad (35)$$

$$Difference\ in\ recovery \quad R_{diff.}\% = \left\{\frac{R_{at\ 100\ Pa} - R_{at\ 3200\ Pa}}{R_{at\ 100\ Pa}}\right\} * 100 \qquad (36)$$

$$Difference\ in\ non-recoverable\ compliance \quad J_{nr(diff.)}\% = \left\{\frac{J_{nr\ at\ 3200\ Pa} - J_{nr\ at\ 100\ Pa}}{J_{nr\ at\ 100\ Pa}}\right\} 100 \qquad (37)$$

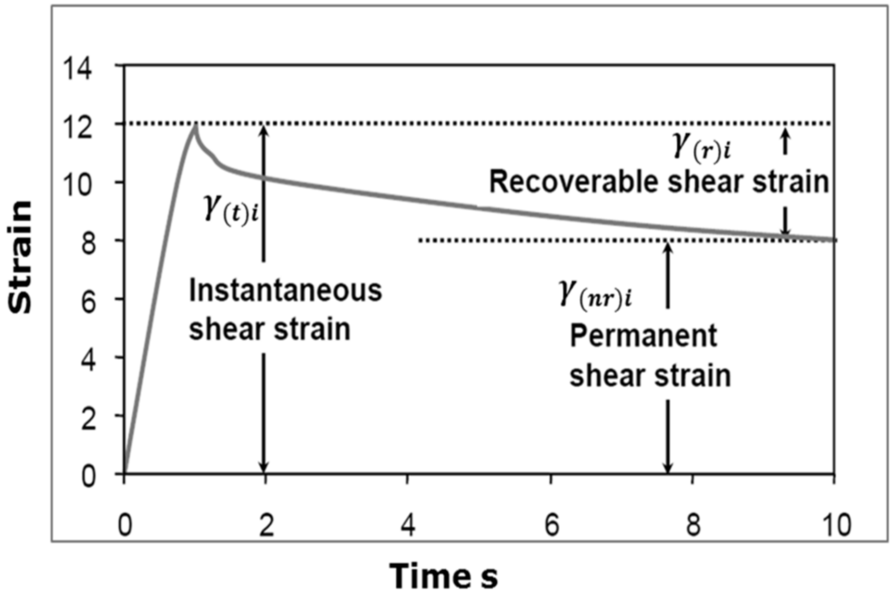

Fig. 15 A typical one cycle of creep-recovery

Where: Recovery % is average recovery of the 10 cycles tested at 100 Pa or 3200 Pa, $\gamma_{(r)i}$ is the recovered strain from the end of the 9 second recovery portion, $\gamma_{(nr)i}$ is the nonrecovered strain from the end of the 9 second recovery portion, $\gamma_{(t)i}$ is the creep strain at the end of the 1 second of creep portion and J_{nr} is average nonrecoverable compliance of cycles tested at 100 Pa or 3200 Pa.

The nonrecoverable creep compliance, J_{nr}, is strongly recommended as an alternative to the current SHRP parameter G*/sin δ [65]. The J_{nr} has the ability to predict the improvement imparted by modification and it is suitable for specification to both neat and modified bitumen [66]. Measuring the J_{nr} of binders at high stresses that are not within the linear viscoelastic region is potentially better to capture the rutting behaviour in mixtures [32]. The binder grade at specific climatic temperature can also be classified based on traffic desingation and loading rate according to AASHTO M19 as shown in Table 1.

Table 1. AASHTO Designation of Jnr at stress level of 3.20 kPa

Traffic level (ESALs) and loading rate	Designation category	Jnr value (1/kPa)
>30 million and <20 km/h	(E) Exteremly high traffic loading	0.0 to 0.5
>30 million or <20 km/h	(V) Very high traffic loading	0.5 to 1.0
10 to 30 million or 20 to 70 km/h	(H) High traffic loading	1.0 to 2.0
<10 million and > 70 km/h	(S) Standard traffic loading	2.0 to 4.0

The J_{nr} is very sensitive to both temperature and stress level, and the stress dependency is more apparent with modified bitumen. For some highly polymer modified bitumens, the 9s recovery may not be sufficient to get the elastic strain portion fully recovered. In that case, the residue of delayed elastic strain would add to the viscous component resulting in decreasing both the peak strain value and its nonrecovered strain value in every subsequent cycle [68]. It is crucial to define the stress level that should be used to rank the binders in term of their rutting resistance. Literature suggests that the stress level is defined by conducting MSCR at multiple stress conditions and then select the most appropriate stress level that relates most to mixtures and field performance [66, 80, 81]. Additionally, the delayed elastic properties of cross-linked elastomers should be taken into consideration and it should be ensured that all elastic strain is fully recovered during the 9s. Otherwise, an extended recovery time should be considered.

5. Discussion

The goal of highway authorities and the asphalt paving industry is to assure a durable pavement that serves traffic in an acceptable serviceability state. This requires investigating enhanced materials to satisfactorily withstand the increased traffic density and axle loads. Modifying the base bitumen is a common way for improving the mechanical properties of conventional materials. However, the modified binders need to be appropriately designed, produced and constructed; otherwise, a counterproductive result could arise with pavement performance being inferior to conventional asphalt. An improved product development procedure is, therefore, required to develop superior modified binders. In this work, different test methods and parameters for characterising the binders in terms of fatigue cracking and rutting, have been addressed and discussed in detail. The current literature will provide appropriate illustrations for the researchers and bitumen industry to understand the mechanical properties of binders that are relevant to the pavement's main functions. Also, the material selection in terms of the variables related to the modification of bitumen will be appropriately identified.

Although many different modifiers have been used in bitumen modification, over 90% of modified binders can be classified as polymer modified bitumen while the rest are modified by other examples of modifiers such as recycled rubber, waxes based additives and chemical additives [84]. Generally, the polymer modified bitumens tend to have high viscosities at high temperatures posing workability difficulties during the production of asphalt mixtures. Therefore, several studies have been conducted to study the feasibility of combining the polymer modified bitumens with WMA additives. In the light of current literature, the next sections will discuss the effect of modifiers (elastomeric and plastomeric polymers, recycled crumb rubber, Sasobit and other chemical modifiers) on fatigue and rutting related properties.

5.1 The effect of bitumen modification on fatigue related properties

Considerable research in bitumen modification has been undertaken to improve the resistance of binders to fatigue cracking and other types of pavement distresses. Modification of bitumen is important to enhance the strength and elasticity of bitumen at high in-service temperatures while maintaining adequate flexibility at low temperatures. The modification by polymers can impart desirable physical properties to the base bitumen through forming a 3D cross-linking network. The properties of resultant modified binders have been shown to vary depending on the type of modifier, modifier content, mixing conditions (temperature, mixing time, shear intensity), and the source of base bitumen. Moreover, the test conditions as well as the theoretical method that is used to analyse fatigue data, can give different prospect about the fatigue performance. Table 2 summarises different studies that were conducted to study the performance behaviour of bituminous materials. The table provides useful information to researchers and industry in terms of the effect of modifier, analysis method and main findings of each study.

Table 2. The effect of different modifiers on fatigue performance of binders

Reference	Modifier	Testing method and analysis	Main findings
Botella, R., F. E. Pérez-Jiménez, and R. Miró [9]	Polymer modified bitumen	Using the concept of Linear Amplitude Sweep (LAS) test by applying vertical displacement signal to cylindrical binder specimens while recording the	The polymer modified bitumen showed the slowest degradation rate where polymer bonds were less prone to failure than other unmodified bitumens. It also showed the highest strain levels at failure

		resultant load test. The maximum dissipated energy density was used to define the failure strain	which can be translated into better fatigue resistance.
Canestrari, Francesco, et al. [85]	Styrene-butadiene-styrene (SB) radial polymer at three contents (1.8%, 2.8%, and 3.8%) by bitumen weight	Time sweep tests with multiple rest periods (30 min) to allow the occurrence of self-healing. The stiffness recovery of the material was monitored to evaluate the self-healing potential.	The self-healing potential is improved by higher polymer amount based on the cumulative self-healing contribution parameter (N_{fH}) which basically represents the number of load cycles that binder can recover after several rest periods (virtually infinite). Also, higher polymer contents can lead to higher thixotropy and that can contribute to a quick recovery of the internal microstructure.
Santagata, Ezio, et al. [51]	Styrene-butadiene-styrene (SBS) modified binder at low (2-3%) and high (4-6%) polymer dosage	Time sweep test using the DSR and the analysis was based on the dissipated energy ratio (DER) approach. The cohesive healing was evaluated by introducing an intermediate single long rest period at fixed levels of damage.	Modification by high amount of SBS resulted in significant increase in fatigue life when fatigue failure is taken at the peak of DER. However, the SBS polymer exhibited inferior fatigue properties to unmodified ones when the fatigue failure is taken at 50% decrease in the initial stiffness. Healing performance of binders appeared to be significantly enhanced by high polymer modification.
Lee, Soon-Jae, et al. [86]	Recycled crumb rubber modifier (CRM)	Measuring the rheological properties of binders using the DSR	Adding Crumb rubber particles decreases the $G*\sin\delta$ at intermediate temperatures indicating better fatigue resistance. The temperature susceptibility of binder is also improved by rubber particles.
Singh, Dharamveer, et al. [87]	Elvaloy (Elv) + polyphosphoric acid (PPA) modified binder containing three WMA additives (water (Advera), chemical (Evotherm), and wax (Sasobit) based additives) with and without lime.	The linear amplitude sweep (LAS) tests using a viscoelastic continuum damage (VECD) approach.	The addition of Elv+PPA together with Sasobit can enhance the fatigue life of binder. The Advera and Evotherm have negative effect on fatigue life. Also, the addition of lime decreased the fatigue life and failure strain of binder.
Yao, Hui, et al. [88]	non-modified nanoclay (hydrophilic); and polymer modified nanoclay (hydrophobic and organophilic modified by polysiloxane) were used at 2% and 4% by the weight of bitumen to modify a control asphalt PG 58-34.	Superpave binder tests by means of DSR to characterize the viscous and elastic behaviour of bitumen	Adding 4% of polymer modified nanoclay can reduce the dissipated energies per load cycle indicating good resistance ability to fatigue cracking. On the opposite, the addition of non-modified nanocaly had negative effect on fatigue cracking. Polymer modified nanoclay increases the recovery ability of bitumen while the non-modified nanoclay decreases the recovery ability of bitumen
Das, Aditya Kumar, and Mahabir Panda [89]	Sulphur at 1%, 2%, 3%, 4% and 5% by weight of bitumen	Rheological characterization of bitumen using DSR	As the sulphur content increases the G* increases and phase angle decreases. However, the rate of change is only marginal after 3% of sulphur content. The $G^*.\sin\delta$ fatigue parameter at 2% of sulphur showed the lowest value compared to 0% and 3% of suphur.
Zhou, Fujie, et al. [18]	Poly phosphoric acid (PPA), Styrene-butadiene-styrene (SBS), crumb tyre rubber (CRM)	Different fatigue testing (Superpave fatigue parameter $G^*\sin\delta$, DENT, LAS, MSCR) were	$G^*\sin\delta$ ranking was (SBS> CRM> PPA> neat bitumen); DENT ranking was (SBS> neat bitumen> PPA> CRM); LAS ranking was (SBS>

		performed to rank the different modified binders.	CRM> PPA> unmodified bitumen); MSCR ranking was (SBS> CRM> PPA> neat bitumen). However, only the DENT test provided exactly the same ranking as the push pull asphalt mix fatigue test
Paliukaite, M., et al. [90]	Investigating the effect of adding recycled engine oil on neat bitumen and polymer modified binders containing different contents of SBS	DENT test to measure the essential work of fracture and critical crack tip opening displacement (CTOD)	Although adding the engine oil seemed to slightly increase the Superpave grade spans of binders, it significantly impaired the fracture properties (w_e and CTOD). Polymer modification provided major improvements in ductile strain tolerance and, hence, a reduction in cracking distress
Subhy, Ayad, et al. [61]	Recycled crumb rubber, and Sasobit pre-treated crumb rubber	DENT test to study the essential work of fracture and critical crack tip opening displacement (CTOD)	Generally, the addition of rubber resulted in better fracture properties. However, pre-treatment with Sasobit reduce the fracture parameters (w_e and CTOD). Applying the concept of partitioning the total fracture work of energy gave different ranking order to the total fracture energy

5.2 The effect of bitumen modification on rutting related properties

The viscoelastic properties of binders at high temperatures play a key role in determining the rutting resistance of flexible pavement. Even though there have been many comprehensive reviews investigating those characteristics for unmodified bitumens, there have been still limited studies conducted on modified bitumens. For unmodified bitumens, a correlation between the linear viscous component of a bitumen’s behaviour and pavement rutting performance, has been well established [27, 68, 72, 73]. However, this correlation has tended to break down with modified bitumens. It is believed that the considerable sensitivity of modified binders to different stress/strain levels and rate is behind this lack of correlation [66, 80, 81]. Several research works have been implemented to study the effect of different modifiers on the rheological properties of binders at high temperatures. Table 3 summarises these studies and provides general understanding about the effect of different modifiers on the rutting resistance of modified binders.

Table 3. The effect of different modifiers on rutting performance of binders

Reference	**Modifier**	**Testing method and analysis**	**Main findings**
Saboo, N., et al. [91]	Styrene butadiene-styrene (SBS) and ethylene vinyl acetate (EVA) were added at 3% and 5% by binder weight, respectively.	The rutting resistance of different binders were evaluated using $G^*/\sin\delta$, $G^*/(1-(1/\sin\delta \tan\delta))$, ZSV and Jnr. The rutting parameters of binders were then	The modified binders had better rutting properties than neat binders according to the standard laboratory testing. EVA modified binder was found to be the most rut resistant binder. Among the binder rutting parameters, the Jnr from MSCR test

		correlated with the rut depth of mixes using the Wheel rut testing.	was found to correlate more accurately with the wheel rutting test of mixes
Cardone, F., et al. [92]	An elastomer of styrene–butadiene–styrene (SBS) and a plastomer of polyolefin (PO), at three different percentages (2%, 4% and 6% by bitumen weight)	Frequency sweep tests over a range at different temperatures from 4 to 82 C with step of 6 C. the Cross model and the Carreau model were used to predict the zero s/hear viscosity value	The addition of SBS or PO increased the stiffness (complex modulus) and the elastic properties of the material (lower phase angle) at high temperatures. At lower polymer content (2%), SBS modified bitumen gave higher ZSV compared to PO modified bitumen. At higher polymer content (6%), the viscoelastic response of PO modified bitumen at temperatures higher than 40 C became highly shear rate dependent and formed a highly structured polymer phase corresponded with sharp decrease in the phase angle.
Kumar, Rajiv, et al. [93]	WMA additives included (sasobit, evotherm and rediset) were used at 3% for Sasobit, 0.5% for Evotherm and 3% for Rediset to modify a neat bitumen and SBS modified bitumen.	Multiple stress creep and recovery (MSCR) test was done at temperature range of 30–70 C	The addition of Sasobit gave maximum improvement for both neat bitumen and SBS modified bitumen in terms of Jnr and recovery percent followed by Evotherm. Rediset had negative effect on rutting performance of binders as it led to increase the Jnr and decreased the recovery. SBS modified binders had lower Jnr and higher percent recovery in comparison to neat binders.
Subhy, Ayad, et al. [4]	Recycled crumb rubber, Sasobit pre-treated crumb rubber and SBS	The rutting resistance of different binders were evaluated using $G^*/\sin\delta$, $G^*/(1-(1/\sin\delta \tan\delta))$, ZSV, Jnr and recovery percent	The binders were ranked differently when the comparison is made between rutting parameters obtained from the dynamic oscillatory test ($G^*/\sin\delta$, $G^*/(1-1/(\sin\delta \tan\delta))$, ZSV) and the Jnr obtained from the MSCR test. The binder that modified by Sasobit pre-treated crumb rubber exhibited the most stress sensitivity and change from being the one of the best-rut resistant binders among the other modified binders at 0.1 kPa stress level to one of the worst at 12.8 and 25.6 kPa stress levels
Santagata, Ezio, et al. [94]	Linear (30 % styrene) and radial (22 % styrene and 31 % styrene) SBS and Ethylene–Vinyl–Acetat (EVA) were used at 3 to 6 % by weight of the base bitumen	single creep-recovery runs in which creep loading time and recovery time were both set at 900 s. A constant value of shear stress, equal to 100 Pa was applied during the creep loading	For high dosage (6%) SBS modified bitumen with high styrene content (30 and 31 %, linear and radial), a typical rubber-like response was created by the cross-linked polymer structure as indicated by an almost horizontal of plateau of the shear modulus G(t) over a loading time. In the case of the EVA binder, no plateau region is observed at temperatures higher than 40C, since the tougher network of plastomer is partially lost beyond the crystallization temperature of EVA (50 to 80C). The rutting resistance as described by permanent compliance (JP) of binders with 3% of SBS was comparable to that of binders with the 6% of EVA at temperatures higher than 40 C
Zhang, Ran, et al. [95]	Modified bitumen with 1% of SBS were mixed with bio-oil at different dosages of 0%, 5%,	$G^*/\sin\delta$ at high temperatures (50 to 85 C) before and after RTFOT ageing	Before RTFO ageing, the rut parameter decreased with the increase in bio-oil content when the bio-oil content was more than 10%, the effect of bio-oil

	10%, 15% and 20% by binder weight,		increase was almost neutral. However, after RTFOT, bio-oil was very susceptible to ageing and the binder became hard. Thus, bio-binder with high bio-oil content had high G*/sinδ
Wasage, T. L. J, et al. [81]	Styrene–butadiene–styrene (SBS) copolymer and recycled crumb rubber	MSCR experiments were performed using dynamic shear rheometer at different temperatures from 30 to 70C with a loading time of 1 s and an unloading time of 9 s at levels of shear stress from 25 to 25,600 Pa.	The Jnr of SBS and crumb rubber modified binders were found to be very sensitive with the applied stress. The rank of binders was found to change with the applied stress level and test temperature. However, the best correlation between Jnr and rut depth was obtained at the high stress levels of the MSCR test

6. Conclusions

The Dynamic Shear Rheometer (DSR) is widely used to measure fundamentally the viscoelastic response of binders at various loading rates and temperatures. Most of the fatigue and rutting testing methods for binders, adopted in this work, are accomplished using the DSR. The literature review has revealed that using only a single binder property cannot adequately describe the true binder contribution related to asphalt mixture or pavement performance. Bituminous binders and especially the modified binders have a complex behaviour depending on stress degree and rate. It is important to evaluate the materials using different test methods that involve various strain ranges to assert a realistic performance for the developed materials.

Measuring the mechanical properties of bituminous materials under only small strains does not always provide sufficient information to predict the performance of materials under the damaging circumstances that are normally accompanied by high strain levels and yielding. The resistance properties of materials under these circumstances should be considered in order to develop fundamental and more performance-related characterisations. The fatigue performance testing of binders using the time sweep repeated cyclic loading (TSRCL) tests and fracture testing, offer practical way to evaluate the binders under these circumstances.

It is crucial to evaluate and then appropriately identify the fatigue failure point before commencing the fatigue analysis. The classical approach of a 50% decrease in the initial stiffness is an arbitrary definition and could lead to incorrect analyses. Fundamental approaches, such as using the dissipated energy approach, should be considered to provide a more realistic definition of fatigue failure.

The rutting parameters obtained from the dynamic oscillatory test are not adequate to predict the binder response under high strain levels and yielding that are normally induced within asphalt mixture. In contrast, the MSCR test can capture the rutting properties of binders at multiple stress conditions, and then the selection of the most effective stress condition that induces approximately similar strains as in the asphalt mixture.

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